



Irvine, P.J., Lunt, D.J., Stone, E.J., & Ridgwell, A.J. (2009). The fate of the Greenland Ice Sheet in a geoengineered, high CO<sub>2</sub> world. *Environmental Research Letters*, 4(4), [045109].  
<https://doi.org/10.1088/1748-9326/4/4/045109>

Publisher's PDF, also known as Version of record

Link to published version (if available):  
[10.1088/1748-9326/4/4/045109](https://doi.org/10.1088/1748-9326/4/4/045109)

[Link to publication record in Explore Bristol Research](#)  
PDF-document

This article is published under a CC BY-NC-SA Licence 3.0.

## University of Bristol - Explore Bristol Research

### General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:  
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

## The fate of the Greenland Ice Sheet in a geoengineered, high CO<sub>2</sub> world

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2009 Environ. Res. Lett. 4 045109

(<http://iopscience.iop.org/1748-9326/4/4/045109>)

View [the table of contents for this issue](#), or go to the [journal homepage](#) for more

Download details:

IP Address: 137.222.24.40

This content was downloaded on 28/01/2015 at 08:55

Please note that [terms and conditions apply](#).

# The fate of the Greenland Ice Sheet in a geoengineered, high CO<sub>2</sub> world

Peter J Irvine<sup>1,3</sup>, Daniel J Lunt<sup>1,2</sup>, Emma J Stone<sup>1</sup> and Andy Ridgwell<sup>1</sup>

<sup>1</sup> Bristol Research Initiative for the Dynamic Global Environment, School of Geographical Sciences, University of Bristol, Bristol BS8 1SS, UK

<sup>2</sup> British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK

E-mail: [p.j.irvine@bristol.ac.uk](mailto:p.j.irvine@bristol.ac.uk)

Received 16 October 2009

Accepted for publication 25 November 2009

Published 15 December 2009

Online at [stacks.iop.org/ERL/4/045109](http://stacks.iop.org/ERL/4/045109)

## Abstract

Solar radiation management (SRM) geoengineering has been proposed as one means of helping avoid the occurrence of dangerous climate change and undesirable state transitions ('tipping points') in the Earth system. The irreversible melting of the Greenland Ice Sheet is a case in point—a state transition that could occur as a result of CO<sub>2</sub>-driven elevated global temperatures, and one leading to potentially catastrophic sea-level rise. SRM schemes such as the creation of a 'sunshade' or injection of sulfate aerosols into the stratosphere could reduce incoming solar radiation, and in theory balance, in a global mean, the greenhouse warming resulting from elevated concentrations of CO<sub>2</sub> in the atmosphere. Previous work has highlighted that a geoengineered world would have: warming towards the poles, cooling in the tropics, and a reduction in the global hydrological cycle, which may have important implications for the Greenland Ice Sheet. Using a fully coupled global climate model in conjunction with an ice sheet model, we assess the consequences for the mass balance of the Greenland Ice Sheet of the reorganization of climate patterns by the combination of high CO<sub>2</sub> and geoengineering. We find that Greenland surface temperature and precipitation anomalies, compared to the pre-industrial situation, decrease almost linearly with increasing levels of SRM geoengineering, but that these combine to create a highly non-linear response of the ice sheet. The substantial melting of the Greenland Ice Sheet predicted for four times pre-industrial CO<sub>2</sub> levels is prevented in our model with only a partial application of SRM, and hence without having to fully restore the global average temperature back to pre-industrial levels. This suggests that the degree of SRM geoengineering required to mitigate the worst impacts of greenhouse warming, such as sea-level rise, need not be as extensive as generally assumed.

**Keywords:** geoengineering, Greenland, ice sheet, sunshade, general circulation model, sea level, climate change, radiation balance

## 1. Introduction

It is expected that by the end of the century, global average surface temperatures will have risen by a further 1.5–4 °C, depending on emissions pathway (IPCC 2007). To avoid 'dangerous' climate change (Hansen *et al* 2006) and the occurrence of undesirable and rapid and/or discontinuous state

transitions in the Earth system (known loosely as 'tipping points' (Lenton *et al* 2008)), many authors and international bodies are calling for efforts to limit the temperature rise to a maximum of 2 °C (Hansen *et al* 2006). However, efforts to secure the necessary reductions in CO<sub>2</sub> emissions have so far been mostly unsuccessful and a recent study showed that even relatively ambitious CO<sub>2</sub> reduction targets may fail to prevent an eventual 2 °C temperature rise (Weaver *et al* 2007).

<sup>3</sup> Address for correspondence: School of Geographical Sciences, University of Bristol, University Road, Bristol BS8 1SS, UK.

One of the already observable consequences of greenhouse warming is a reduction in the volume of the Greenland Ice Sheet (GrIS) (Alley *et al* 2005, Krabill *et al* 2004, Rignot *et al* 2008) and an associated sea-level rise. For a sustained atmospheric CO<sub>2</sub> concentration of 550 ppm, Alley *et al* (2005) estimate that a near-total melting of the GrIS would eventually occur, albeit highly unlikely to occur in the next century (Pfeffer *et al* 2008). Although there are uncertainties regarding where the CO<sub>2</sub> threshold for complete melting lies (e.g. Lunt *et al* 2009) as well as the timescale at which the melting would take place, the extreme social and economic consequences of even a fraction of the maximum potential sea-level rise of 7.3 m (Bamber *et al* 2001) occurring, clearly warrant an urgent assessment of whether mitigation strategies exist for melting of the GrIS and whether they would be effective.

Geoengineering has been proposed as a means to avoid dangerous levels of climate change and tipping points (such as large-scale melting of the GrIS) being crossed (Royal Society 2009, Irvine and Ridgwell 2009). Of particular interest has been the potential for modification of the solar radiation budget via the creation of a solar 'sunshade' (Angel 2006) or injection of sulfate aerosols into the upper atmosphere (Crutzen 2006) as a means to restore global mean temperatures to pre-industrial levels. A feasibility study of the sunshade idea has been conducted and concluded that the idea is possible but incredibly expensive (Angel 2006). Cooling by injecting sulfate aerosols into the stratosphere may be much more achievable; it has been calculated that 2 Tg of sulfur particles, forming sufficiently small aerosols, could offset a doubling of CO<sub>2</sub> levels from current levels (Rasch *et al* 2008). The cost to deliver 1 Tg of sulfate aerosol precursor to the stratosphere may be as low as \$225 million per year if high altitude military refueling jets were refitted for the job (Robock *et al* 2009). The effects of injecting sulfate aerosols would go beyond cooling the climate; there would be an increase in the diffuse fraction of direct light, reducing the effectiveness of focusing solar power, whitening the sky and increasing plant productivity (Robock *et al* 2009, Mercado *et al* 2009); the sulfate aerosols would also lower ozone levels by providing more surface area for ozone-destroying reactions to take place on (Tilmes *et al* 2008, Rasch *et al* 2008). SRM geoengineering would have no direct effect on CO<sub>2</sub> levels; ocean acidification and the CO<sub>2</sub> fertilization of plants would remain (Matthews *et al* 2009, Leakey 2009).

However, returning global mean temperatures to pre-industrial levels does not *a priori* imply that the GrIS would be safeguarded. This is because these types of solar radiation management (SRM) do not provide a perfect cancellation of global warming and restoration of a pre-industrial climate. Instead, due to differences in the spatial distribution of solar and CO<sub>2</sub> forcing, the tropics tend to end up cooler and the poles warmer than in pre-industrial times, even when temperature is restored at the global mean (Lunt *et al* 2008b, Govindasamy and Caldeira 2000, Matthews and Caldeira 2007). As such, it is possible that SRM would not be effective against sea-level rise, as both the Greenland and Antarctic ice sheets would likely remain significantly warmer than pre-industrial times.

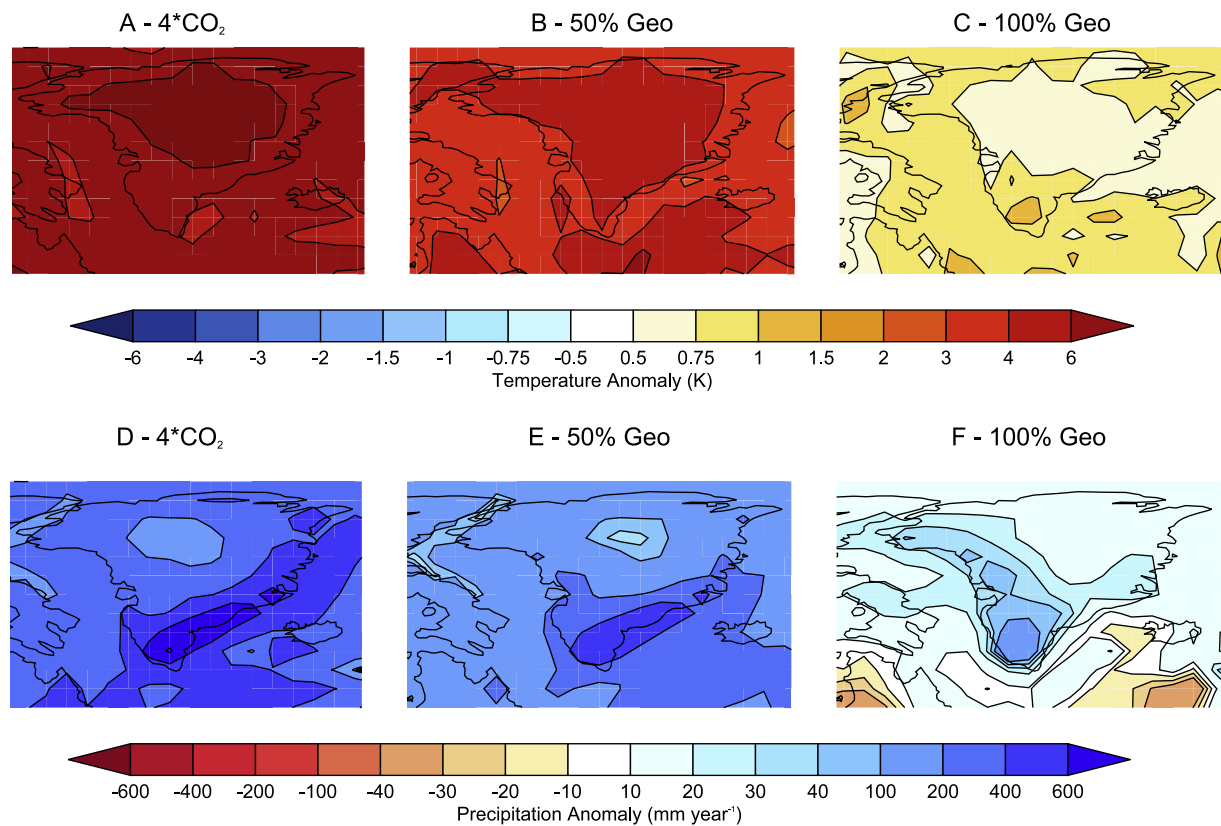
In this paper, we investigate the efficacy of SRM geoengineering in mitigating against sea-level rise from the

GrIS and specifically in the context of its long-term mass balance. We also estimate the minimum level of SRM geoengineering required to avert a potential tipping point associated with the GrIS and the associated sea-level rise. However, our analysis excludes contributions to sea-level rise from the Antarctic ice sheet and from the thermal expansion of the oceans.

## 2. Methodology

To assess the response of climate to greenhouse forcing and SRM geoengineering, we use the fully coupled atmosphere–ocean UK Met Office GCM, HadCM3L (Cox *et al* 2000). HadCM3L has a horizontal resolution of 3.75° longitude by 2.5° latitude in the atmosphere and ocean, 19 vertical levels in the atmosphere and 20 vertical levels in the ocean. It consists of a hydrostatic primitive-equation atmosphere, with parameterizations for sub-gridscale processes such as convection (Gregory and Rowntree 1990). The ocean includes parameterizations of eddy mixing (Gent and McWilliams 1990), and a dynamic-thermodynamic sea-ice scheme (Cattle and Crossley 1995). The configuration of the climate model we use is identical to that described by Lunt *et al* (2008b). A version of the model with increased ocean resolution (HadCM3) has been extensively tested (Gordon *et al* 2000) and performs well relative to other GCMs according to a variety of metrics (IPCC 2007, Covey *et al* 2003).

Using this model we carried out twelve 400-year climate model simulations, all initialized from the end of a spin-up totaling more than 1000 years, with the final 100 years used to calculate the climatological averages. The first is a pre-industrial control ('Pre'), the second has atmospheric CO<sub>2</sub> set at 1120 ppmv, four times the pre-industrial value (4 × CO<sub>2</sub>), and the other ten simulations have 4 × CO<sub>2</sub> and a reduced solar constant scaled according to the assumed degree of SRM geoengineering. The pre-industrial climate has been chosen as the reference state as the GrIS was stable under these conditions and is beginning to melt under modern conditions (van den Broeke *et al* 2009). For the reduced solar constant simulations; full SRM geoengineering ('100%Geo') has the solar constant reduced such that the global annual mean 2 m air temperature was as close as possible to that of the Pre simulation, the other nine simulations have the solar constant reduced by a fraction of this value from 10% to 90% in increments of 10%. The reduction in solar constant for 100% SRM geoengineering was found by carrying out a number of preparatory simulations with improving estimates of the required reduction, as in Lunt *et al* (2008b). As a result, simulation 100%Geo has a solar constant 57 W m<sup>-2</sup> less than that of Pre, a reduction of 4.2%. For comparison, (Govindasamy *et al* 2003) found that they required a reduction of 3.6% to offset a four times increase in CO<sub>2</sub>. The radiative effect of stratospheric sulfate aerosols on the climate can also be approximated fairly well using a global reduction in insolation. For instance, Brovkin *et al* (2009) find small differences in the radiative forcing effect for an even distribution of aerosol, while Robock *et al* (2008) observe that



**Figure 1.** (a)–(c) shows the summer temperature anomaly with pre-industrial times for the  $4 \times \text{CO}_2$ , 50%Geo and 100%Geo simulations respectively. (d)–(f) show the annual precipitation anomalies for the same simulations.

a fairly even distribution of aerosols is possible for a constant injection of sulfates into the tropical stratosphere.

From the GCM simulations, we calculate the temperature and precipitation anomalies relative to the control simulation, and combine these anomalies with an observed climatology to drive an off-line ice sheet model—Glimmer (Rutt *et al* 2009). Glimmer (v. 1.0.4) is a three-dimensional thermomechanical ice sheet model, configured over the Greenland region. The core of the model is based on the ice sheet model described by (Payne 1999). The model resolution is 20 km, and is configured as described in Lunt *et al* (2008a, 2009). Glimmer performs well against established EISMINT benchmarks and against other analytical solutions for ice flow (Rutt *et al* 2009). However, due to the use of the shallow-ice approximation (Hutter 1983), it does not well simulate fast-flowing ice streams and has a relatively simple treatment of basal sliding, basal hydrology, and calving at marine margins. The implications of some of these shortcomings are discussed later in the paper. The last 100 years of the climate simulations are used to generate an annual mean and half-range climatology—Glimmer then applies a sinusoidal seasonal and diurnal cycle to this climatology and this drives the ice sheet model for the duration of the experiment. The Glimmer ice sheet model uses an anomaly method to accommodate for biases in the driving climatology; the pre-industrial is the control simulation with all other simulations applying an anomaly to the standard (i.e., observed) climatology. For each GCM simulation, the ice sheet model is run for 50 000 years, allowing most of the simulations

to come to equilibrium with the driving climatology. Three simulations required more time to reach equilibrium; these were run for a further 50 000 years. (A full description of the off-line coupling of the climate model and ice sheet model can be found in Lunt *et al* (2008a, 2009).)

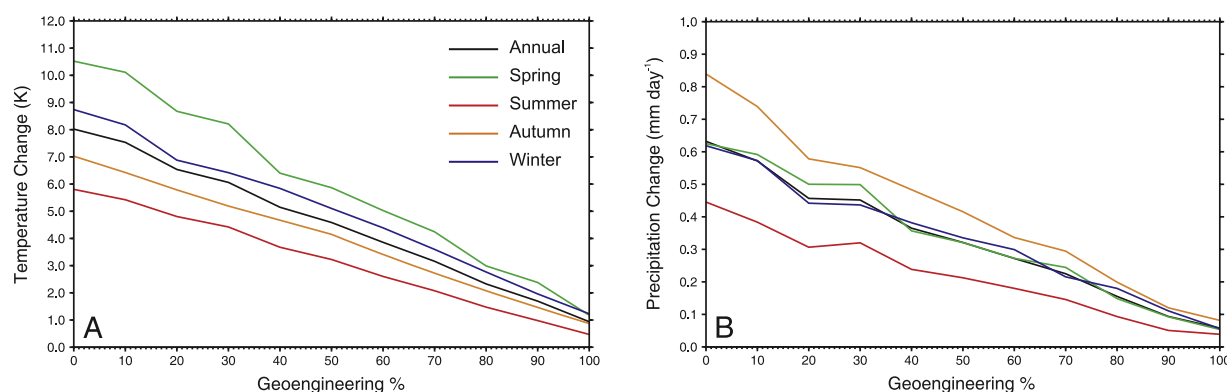
### 3. Results

The mass balance of an ice sheet, under a positive degree day formulation, depends on the net difference between the rate of snow accumulation and the melt rate, and hence the balance between precipitation and temperature across the region and season of ablation. Increases in summer temperatures have the largest impact on the mass balance of ice sheets as this is the time when air temperatures are highest, the ablation zone largest, and surface ice melt rates most rapid. The total amount of precipitation that falls on the ice sheet throughout the year determines the accumulation of snow mass.

In the absence of SRM geoengineering and hence an unmitigated  $4 \times \text{CO}_2$  climate, the center of the GrIS has a summer average temperature over  $6^\circ\text{C}$  warmer than in the pre-industrial with no region experiencing a temperature less than  $4^\circ\text{C}$  warmer (figure 1(a)). However, annual precipitation also increases across Greenland, with increases of over  $6 \text{ m year}^{-1}$  along some of the eastern coast and towards the southern tip (figure 1(d)).

Both the patterns as well as magnitude of temperature and precipitation anomalies change as a function of the degree of





**Figure 2.** Seasonal and annual anomalies relative to pre-industrial times for different levels of SRM geoengineering, averaged over Greenland. (a) 2 m air temperature anomaly, (b) precipitation anomaly.

SRM geoengineering (figure 1). Figures 1(b) and (c) show the annual average temperature anomalies for the 50%Geo and 100%Geo simulations, illustrating how climatological patterns respond to the degree of SRM geoengineering intervention. The annual mean surface air temperature anomalies in Greenland are significantly reduced with the application of 100% SRM geoengineering, although the island remains warmer than in the pre-industrial period. A temperature increase of at least 0.5 °C persists across Greenland with the northern and southern coasts experiencing a warming of 0.75 °C and the southern tip has over 1 °C of warming. The 50%Geo simulation shows an approximately intermediate warming compared with pre-industrial and 100%Geo, with at least 3 °C of warming across most of the island. For both: 50%Geo and 100%Geo, Greenland experiences a smaller increase in precipitation than for 4 × CO<sub>2</sub> (all compared with pre-industrial). This increase in precipitation over Greenland for 100%Geo is despite the global mean reduction in precipitation found in this study and other studies of sunshade and stratospheric aerosol geoengineering (Lunt *et al* 2008b, Robock *et al* 2008, Bala *et al* 2008) in which on a global scale, the reduced insolation causes a reduction in latent heat flux, and consequently evaporative flux, from the land and sea surfaces reducing the intensity of the global hydrological cycle. The regional precipitation increases we find in all of the simulations are focused to the south of the island.

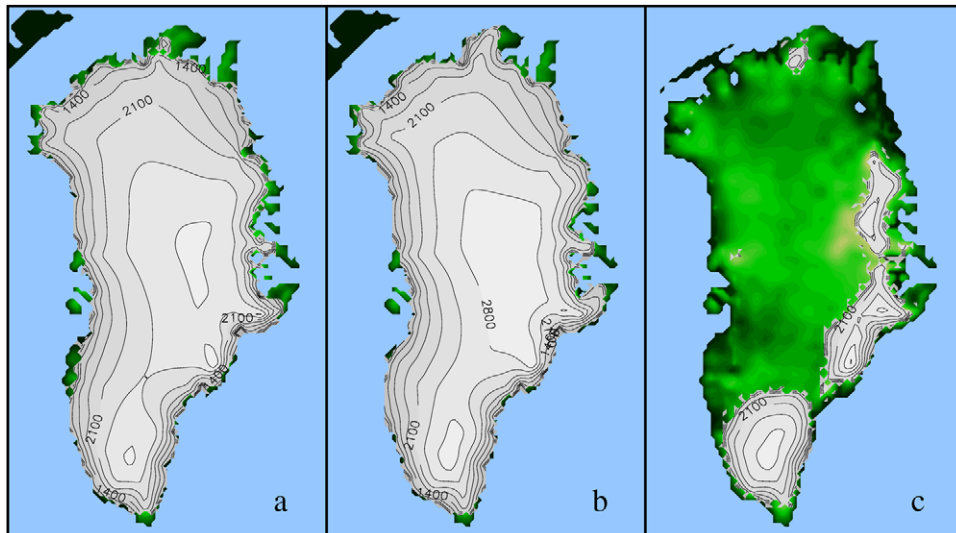
Averaging the temperature anomalies over the area of Greenland, we find an approximate linear relationship with the level of SRM geoengineering (figure 2(a)). For temperature, the annual average is 8 °C warmer for 4 × CO<sub>2</sub>, decreasing almost linearly to a 1 °C positive anomaly for the 100%Geo simulation. This relationship also holds for the individual seasonal changes although the slope varies. The increase in summer temperature is 6 °C at 4 × CO<sub>2</sub>, which is below the annual average warming whereas the spring temperature shows the greatest departure from pre-industrial with an anomaly of 10.5 °C. The climate changes in the arctic are affected by the ice-albedo effect, as sea-ice cover and snow cover is reduced; there is an increased absorption of sunlight and so regional warming (IPCC 2007). There is also a reduction in the insulation of the Arctic Ocean as sea-ice cover retreats, this

leads to an increased heat flux from the ocean in the autumn, which warms the atmosphere (Serreze *et al* 2009).

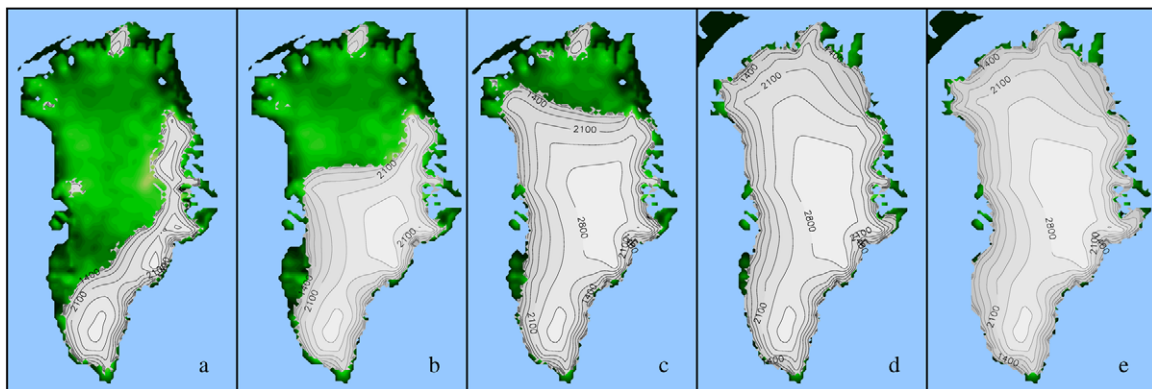
Similar responses to the degree of SRM geoengineering are apparent for the precipitation anomalies (figure 2). With no SRM geoengineering the annual change in precipitation is 0.63 mm day<sup>-1</sup> or 228 mm year<sup>-1</sup>, which decreases roughly linearly with increasing SRM geoengineering level, with a positive anomaly of 21 mm year<sup>-1</sup> for 100%Geo (figure 2(b)). The greatest increase in precipitation occurs in the autumn with 76 mm season<sup>-1</sup> more in the un-geoengineered case than in the pre-industrial period. Winter and spring precipitation anomalies closely track the annual mean.

To assess the implications of a change in climate over Greenland on the global sea-level an ice sheet model must be used. Simply inferring sea-level changes from just the climate model output is insufficient as it is impossible to capture important properties of ice sheets like the altitude–temperature feedback, where the altitude of the ice sheet keeps the surface cool and prevents the melt of accumulated snow. The response of the GrIS mass to changes in the climate also has the potential to be non-linear with possible hysteresis due to the large positive altitude–temperature feedback.

Figure 3 shows the predicted ice sheet response, calculated by running Glimmer to equilibrium, for the pre-industrial and 4 × CO<sub>2</sub> simulations, as well as the observed modern ice sheet. In the pre-industrial control experiment (figure 3(b)), the ice volume is over-estimated compared with observations (figure 3(a)), giving a sea-level equivalent of 8.6 m compared with the literature value of 7.3 m (Bamber *et al* 2001). This is a common deficiency in current ice sheet models due, in part, to the lack of an accurate representation of ice dynamics (Ridley *et al* 2005, Huybrechts and de Wolde 1999, Ritz *et al* 1997, Greve 2000). Sea-level equivalents given here are estimated using the fractional ice sheet mass difference to calculate a sea-level rise equivalent and hence account for this systematic overestimation. Figure 3(c) shows the ice sheet height and extent at equilibrium after being forced by the 4 × CO<sub>2</sub> climatology; the ice sheet is only 12.8% of its original mass, equivalent to a sea-level rise of 6.4 m. The remnants of the ice sheet are located at the high altitude regions on the eastern coastline and on the southern tip. Other authors have noted that a similar, near-total, melting of the GrIS at four times



**Figure 3.** (a) Observed modern ice sheet, (b) simulated pre-industrial ice sheet, (c) ice sheet at  $4 \times \text{CO}_2$ .



**Figure 4.** Shows the equilibrium ice sheet extent predicted for different levels of geoengineering: (a) 20%Geo, (b) 30%Geo, (c) 40%Geo, (d) 60%Geo, (e) 100%Geo. For (b), (d) and (e) the ice sheets reach equilibrium after 50 000 years, For (a) and (c) 100 000 years were run to reach equilibrium.

pre-industrial  $\text{CO}_2$  is likely (Gregory *et al* 2004). However, the pattern of ice sheet remnants differs from others in that ice is present in the southern tip of the island (Alley *et al* 2005, Ridley *et al* 2005).

We now turn to the predicted extent and height of the ice sheets generated under different levels of SRM geoengineering (figure 4). At 20% SRM Geoengineering (figure 4(a)), the extent and coverage of the ice sheet is slightly larger than the un-geoengineered case, with the remnants of the ice sheet more inter-connected. At 30% (figure 4(b)) and 40% (figure 4(c)) SRM geoengineering there is a partial ice sheet with losses in extent to the north of the island and losses in altitude for the 30%Geo case. The ice sheet is effectively at full height and coverage for 60% SRM geoengineering and above (figures 4(d)–(e)), and a pre-industrial ice sheet is maintained.

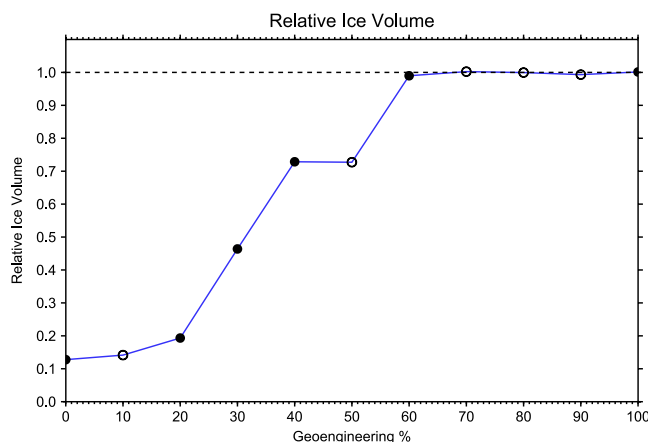
In contrast to the temperature and precipitation anomalies (figure 2), the response of the volume of the GrIS to the level of SRM geoengineering is highly non-linear and displays a step-like behavior (figure 5). The ice volume is only slightly increased for 10%Geo and 20%Geo compared with

$4 \times \text{CO}_2$ , increasing for 30%Geo and again at 40%Geo; 50%Geo produces the same ice sheet volume as 40%Geo, and at 60%Geo and at greater degrees of SRM geoengineering, the ice sheet volume remains at roughly the pre-industrial value.

#### 4. Discussion and conclusions

For all of the SRM geoengineering simulations and the  $4 \times \text{CO}_2$  case, the climate of Greenland is warmer and wetter than the pre-industrial period. Averaged over Greenland, the temperature and precipitation anomalies decrease almost linearly with increases in the level of SRM geoengineering but with residual warming and wetting of Greenland at full SRM geoengineering. This contrasts with the global picture, in which average surface air temperature is exactly the same as in the pre-industrial period for full SRM geoengineering and there is a net global reduction in precipitation (Lunt *et al* 2008b).

In agreement with previous work (Ridley *et al* 2005), the consequence of unmitigated ( $4 \times \text{CO}_2$ ) climate change to the mass balance of the GrIS are drastic enough to eventually



**Figure 5.** Fraction of ice volume, relative to pre-industrial times, at different levels of SRM geoengineering. The filled circles highlight the ice sheets which are shown in figures 3 and 4, unfilled circles are not displayed in other figures.

melt it almost entirely. By applying increasing degrees of SRM geoengineering and hence reductions in the incoming solar radiation, climate change under  $4\times$  atmospheric  $\text{CO}_2$  is progressively mitigated at the global mean and over Greenland. However, the approximately linear change in the climate conditions over Greenland are not reflected in the ice sheet response.

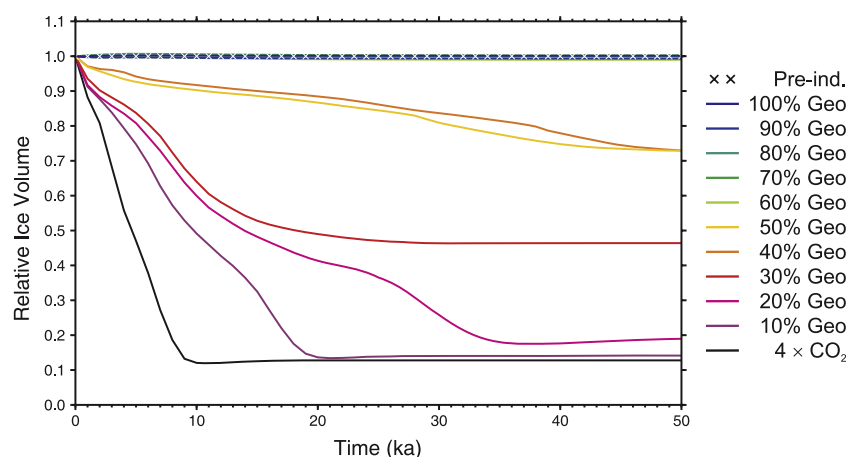
We interpret the varying differential responses to the degree of SRM geoengineering as reflecting the existence of multiple thresholds and stable states in the ice sheet, illustrated by the time-dependent behavior of ice sheet volume in figure 6. For 20%, 40% and 50% SRM geoengineering the ice sheet has not quite reached equilibrium by 50 000 years however they are all within 0.5% of their final volume. For 60%Geo and above a similar evolution is seen as for the pre-industrial period. The 40%Geo and 50%Geo ice sheets follow similar trajectories, with 40%Geo having a greater volume than 50%Geo, but with both stabilizing at a relative ice volume of just over 70% of the pre-industrial ice sheet. The 20%Geo and 30%Geo cases follow similar trajectories until around 20 000 years at this

point the ice sheet in the 20% SRM geoengineering climate begins to collapse, ending slightly larger than the  $4\times\text{CO}_2$  case; the 30%Geo case stabilizes and a partial ice sheet remains. The 10%Geo and the  $4\times\text{CO}_2$  cases both collapse rapidly leaving a residual ice sheet with just over 10% of the pre-industrial control volume.

The ice sheet hence responds in a step-like manner to the SRM geoengineered changes in the climate; for low levels the ice sheet almost completely melts, for 30–50% SRM geoengineering a partial ice sheet remains and at levels of SRM geoengineering of 60% or above the ice sheet remains fully intact. We interpret the bifurcation of the evolution of the 20% and 30% SRM geoengineering ice sheets in terms of a positive altitude–temperature feedback, which amplifies the small difference in input climates and causes a run-away melting. Without further simulations it is hard to tell whether the 30% SRM geoengineering ice sheet represents a third stable level or whether it forms part of a continuum of partial ice sheets between 20%Geo and 40%Geo.

Our results suggest that a full SRM geoengineering intervention would prevent the melting of the GrIS and stop the resultant ice-induced sea-level rise. At  $4\times\text{CO}_2$  the melting of the GrIS would contribute 6.4 m to sea-level, for 30%Geo the sea-level rise would be 3.9 m, for 40%Geo and 50%Geo 2 m and at 60%Geo and above no sea-level increase from the GrIS is observed. The changes in sea-level that occur in the first 100 years of the simulations are strongly dependent on the level of SRM geoengineering: for  $4\times\text{CO}_2$  there would be 24 cm, for 40%Geo 6 cm, for 60%Geo 2 cm and for 100%Geo there would be 0.1 cm of sea-level increase. This dramatically non-linear response of the ice sheet highlights the necessity of detailed analysis of the regional impacts of SRM geoengineering schemes.

In interpreting the results presented here it must be borne in mind that the climate and ice sheet models available today have flaws and do not exactly reproduce observed modern climate and ice sheet extent. Many climate models agree on the broad changes in the temperature that would occur at high levels of  $\text{CO}_2$  but there is a large degree of disagreement for regional climate change and for other aspects of climate



**Figure 6.** Evolution of the ice sheet volume, for all the simulations, relative to the equilibrium volume of the pre-industrial control ice sheet. Only the first 50 ka are shown, as the ice sheets have mostly reached equilibrium by this point.



such as cloud cover and precipitation. The UK Met Office Model (HadCM3), which is used in this paper, has a cold bias towards the poles over the Northern Hemisphere land masses (IPCC 2007). However, the Glimmer model uses an anomaly method to calculate the climate to force the ice sheet and hence minimizes the consequences of the cold bias in the climate model.

It is also important to be aware that our simulations are performed without interactive coupling between the ice sheet model and GCM and hence neglecting in particular the ice-albedo feedback, although the ice-altitude feedback is taken into account using a lapse-rate correction. Current ice sheet models also generally lack higher order physics and although able to simulate slow moving ice dynamics adequately they are not yet able to represent the dynamics of fast moving ice streams. Deficiencies of ice sheet models in these areas is currently being addressed, with improvements to ice dynamics (Pattyn 2003), representations of the fast ice streams and ice shelves (Schoof 2006, 2007, Pattyn *et al* 2006), more realistic modeling of the surface mass balance (Bougamont *et al* 2007), and treatments of basal sliding which take into account positive feedbacks (Parizek and Alley 2004, Price *et al* 2008). Recent work has indicated that current loss of mass from the Greenland ice sheet is roughly equally partitioned between surface mass balance changes and changes in dynamics (van den Broeke *et al* 2009). Given the large uncertainties in quantifying future dynamic ice losses at Greenland's marine terminating outlet glaciers, the thresholds determined in this paper for effective SRM geoengineering in the context of the GrIS should be regarded with some caution. In particular, it is likely that ice loss will be greater than predicted by the ice sheet model, resulting in a higher level of SRM geoengineering needed to avert a given sea-level rise.

It has been argued that the predicted changes in the climate caused by SRM geoengineering are not benign. For example, the reduction in global precipitation could have an adverse effect on agriculture, and so partial geoengineering could potentially be a more favorable proposition (Robock *et al* 2008, Bala *et al* 2008). From this study, we find that a partial SRM geoengineering intervention might also prevent the melting of the GrIS and avoid the catastrophic sea-level rises that this would cause. However, the existence of thresholds and multiple states in sub-systems such as the GrIS cautions that regional impacts and climate teleconnections need be studied in detail when assessing SRM geoengineering and determining its efficacy.

## Acknowledgments

PI is funded on a NERC PhD studentship. AR acknowledges support from The Royal Society in the form of a University Research Fellowship. DL acknowledges funding from the British Antarctic Survey and from the RCUK in the form of a Research Fellowship. ES is funded on a NERC PhD studentship.

## References

- Alley R B, Clark P U, Huybrechts P and Joughin I 2005 Ice-sheet and sea-level changes *Science* **310** 456–60
- Angel R 2006 Feasibility of cooling the Earth with a cloud of small spacecraft near the inner Lagrange point (L1) *Proc. Natl Acad. Sci. USA* **103** 17184–9
- Bala G, Duffy P B and Taylor K E 2008 Impact of geoengineering schemes on the global hydrological cycle *Proc. Natl Acad. Sci. USA* **105** 7664–9
- Bamber J L, Layberry R L and Gogineni S 2001 A new ice thickness and bed data set for the Greenland ice sheet 1. Measurement, data reduction, and errors *J. Geophys. Res.-Atmos.* **106** 33773–80
- Bougamont M, Bamber J L, Ridley J K, Gladstone R M, Greuell W, Hanna E, Payne A J and Rutt I 2007 Impact of model physics on estimating the surface mass balance of the Greenland ice sheet *Geophys. Res. Lett.* **34** L17501
- Brovkin V, Petoukhov V, Claussen M, Bauer E, Archer D and Jaeger C 2009 Geoengineering climate by stratospheric sulfur injections: Earth system vulnerability to technological failure *Clim. Change* **92** 243–59
- Cattle H and Crossley J 1995 Modeling arctic climate-change *Phil. Trans. R. Soc. A* **352** 201–13
- Covey C, AchutaRao K M, Cubasch U, Jones P, Lambert S J, Mann M E, Phillips T J and Taylor K E 2003 An overview of results from the coupled model intercomparison project *Glob. Planet. Change* **37** 103–33
- Cox P M, Betts R A, Jones C D, Spall S A and Totterdell I J 2000 Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model *Nature* **408** 184–7
- Crutzen P J 2006 Albedo enhancement by stratospheric sulfur injections: a contribution to resolve a policy dilemma? *Clim. Change* **77** 211–9
- Gent P R and McWilliams J C 1990 Isopycnal mixing in ocean circulation models *J. Phys. Oceanogr.* **20** 150–5
- Gordon C, Cooper C, Senior C A, Banks H, Gregory J M, Johns T C, Mitchell J F B and Wood R A 2000 The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments *Clim. Dyn.* **16** 147–68
- Govindasamy B and Caldeira K 2000 Geoengineering Earth's radiation balance to mitigate CO<sub>2</sub>-induced climate change *Geophys. Res. Lett.* **27** 2141–4
- Govindasamy B, Caldeira K and Duffy P B 2003 Geoengineering Earth's radiation balance to mitigate climate change from a quadrupling of CO<sub>2</sub> *Glob. Planet. Change* **37** 157–68
- Gregory D and Rowntree P R 1990 A mass flux convection scheme with representation of cloud ensemble characteristics and stability-dependent closure *Mon. Weather Rev.* **118** 1483–506
- Gregory J M, Huybrechts P and Raper S C B 2004 Climatology—threatened loss of the greenland ice-sheet *Nature* **428** 616
- Greve R 2000 On the response of the Greenland ice sheet to greenhouse climate change *Clim. Change* **46** 289–303
- Hansen J, Sato M, Ruedy R, Lo K, Lea D W and Medina-Elizade M 2006 Global temperature change *Proc. Natl Acad. Sci. USA* **103** 14288–93
- Hutter K 1983 *Theoretical Glaciology: Mathematical Approaches to Geophysics* (Dordrecht: Reidel)
- Huybrechts P and de Wolde J 1999 The dynamic response of the Greenland and Antarctic ice sheets to multiple-century climatic warming *J. Clim.* **12** 2169–88
- Irvine P and Ridgwell A 2009 'Geoengineering'—taking control of our planet's climate *Sci. Prog.* **92** 139–62
- IPCC 2007 *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed D Q S Solomon, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) p 996

- Krabill W et al 2004 Greenland ice sheet: increased coastal thinning *Geophys. Res. Lett.* **31** L24402
- Leakey A D B 2009 Rising atmospheric carbon dioxide concentration and the future of C<sub>4</sub> crops for food and fuel *Proc. R. Soc. B* **276** 2333–43
- Lenton T M, Held H, Kriegler E, Hall J W, Lucht W, Rahmstorf S and Schellnhuber H J 2008 Tipping elements in the Earth's climate system *Proc. Natl Acad. Sci. USA* **105** 1786–93
- Lunt D J, Foster G L, Haywood A M and Stone E J 2008a Late pliocene Greenland glaciation controlled by a decline in atmospheric CO<sub>2</sub> levels *Nature* **454** 1102–5
- Lunt D J, Haywood A M, Foster G L and Stone E J 2009 The Arctic cryosphere in the mid-pliocene and the future *Phil. Trans. R. Soc. A* **367** 49–67
- Lunt D J, Ridgwell A, Valdes P J and Seale A 2008b 'Sunshade World': a fully coupled GCM evaluation of the climatic impacts of geoengineering *Geophys. Res. Lett.* **35** L12710
- Matthews H D and Caldeira K 2007 Transient climate-carbon simulations of planetary geoengineering *Proc. Natl Acad. Sci. USA* **104** 9949–54
- Matthews H D, Cao L and Caldeira K 2009 Sensitivity of ocean acidification to geoengineered climate stabilization *Geophys. Res. Lett.* **36** 5
- Mercado L M, Bellouin N, Sitch S, Boucher O, Huntingford C, Wild M and Cox P M 2009 Impact of changes in diffuse radiation on the global land carbon sink *Nature* **458** 1014–7
- Parizek B R and Alley R B 2004 Implications of increased Greenland surface melt under global-warming scenarios: ice-sheet simulations *Q. Sci. Rev.* **23** 1013–27
- Pattyn F 2003 A new three-dimensional higher-order thermomechanical ice sheet model: basic sensitivity, ice stream development, and ice flow across subglacial lakes *J. Geophys. Res.-Solid Earth* **108** 2382
- Pattyn F, Huyghe A, De Brabander S and De Smedt B 2006 Role of transition zones in marine ice sheet dynamics *J. Geophys. Res.-Earth Surf.* **111**
- Payne A J 1999 A thermomechanical model of ice flow in West Antarctica *Clim. Dyn.* **15** 115–25
- Pfeffer W T, Harper J T and O'Neel S 2008 Kinematic constraints on glacier contributions to 21st-century sea-level rise *Science* **321** 1340–3
- Price S F, Conway H, Waddington E D and Bindshadler R A 2008 Model investigations of inland migration of fast-flowing outlet glaciers and ice streams *J. Glaciol.* **54** 49–60
- Rasch P J, Tilmes S, Turco R P, Robock A, Oman L, Chen C C, Stenchikov G L and Garcia R R 2008 An overview of geoengineering of climate using stratospheric sulphate aerosols *Phil. Trans. R. Soc. A* **366** 4007–37
- Ridley J K, Huybrechts P, Gregory J M and Lowe J A 2005 Elimination of the Greenland ice sheet in a high CO<sub>2</sub> climate *J. Clim.* **18** 3409–27
- Rignot E, Box J E, Burgess E and Hanna E 2008 Mass balance of the Greenland ice sheet from 1958 to 2007 *Geophys. Res. Lett.* **35** L20502
- Ritz C, Fabre A and Letreguilly A 1997 Sensitivity of a Greenland ice sheet model to ice flow and ablation parameters: consequences for the evolution through the last climatic cycle *Clim. Dyn.* **13** 11–24
- Robock A, Marquardt A, Kravitz B and Stenchikov G 2009 Benefits, risks, and costs of stratospheric geoengineering *Geophys. Res. Lett.* **36** 9
- Robock A, Oman L and Stenchikov G L 2008 Regional climate responses to geoengineering with tropical and arctic SO<sub>2</sub> injections *J. Geophys. Res.-Atmos.* **113** D16101
- Rutt I C, Hagdorn M, Hulton N R J and Payne A J 2009 The Glimmer community ice sheet model *J. Geophys. Res.* **114** F02004
- Royal Society 2009 *Geoengineering the Climate: Science, Governance and Uncertainty* ed J Shepherd, K Caldeira, P Cox, J Haigh, D Keith, B Launder, G Mace, G MacKerron, J Pyle, S Rayner, C Redgwell, A Watson, R Garthwaite, R Heap, A Parker and J Wilsdon (London: The Royal Society)
- Schoof C 2006 A variational approach to ice stream flow *J. Fluid Mech.* **556** 227–51
- Schoof C 2007 Ice sheet grounding line dynamics: steady states, stability, and hysteresis *J. Geophys. Res.-Earth Surf.* **112** F03S28
- Serreze M C, Barrett A P, Stroeve J C, Kindig D N and Holland M M 2009 The emergence of surface-based Arctic amplification *Cryosphere* **3** 11–9
- Tilmes S, Muller R and Salawitch R 2008 The sensitivity of polar ozone depletion to proposed geoengineering schemes *Science* **320** 1201–4
- van den Broeke M, Bamber J, Ettema J, Rignot E, Schrama E, van de Berg W J, van Meijgaard E, Velicogna I and Wouters B 2009 Partitioning recent greenland mass loss *Science* **326** 984–6
- Weaver A J, Zickfeld K, Montenegro A and Eby M 2007 Long term climate implications of 2050 emission reduction targets *Geophys. Res. Lett.* **34** L19703